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HRP Occupant Protection Discipline Overview

J. Somers
M. Gernhardt
N. Newby

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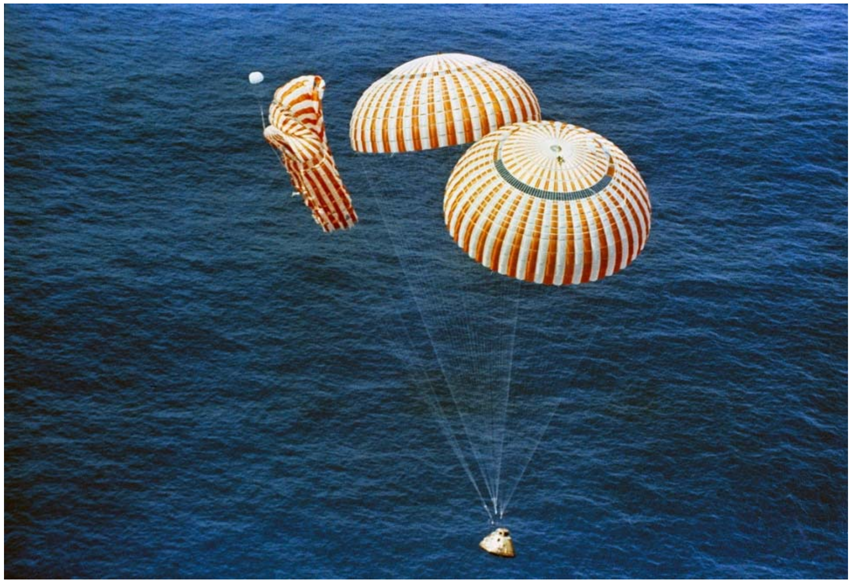
What is Occupant Protection?

Protecting people during “dynamic events.”



Crew Vehicle Comparison

Current System

Soyuz TMA-M

Multi-purpose Crew Vehicle Program

Orion

Commercial Crew Program

SpaceX Dragon

Boeing CCT-100

Sierra Nevada Dream Chaser

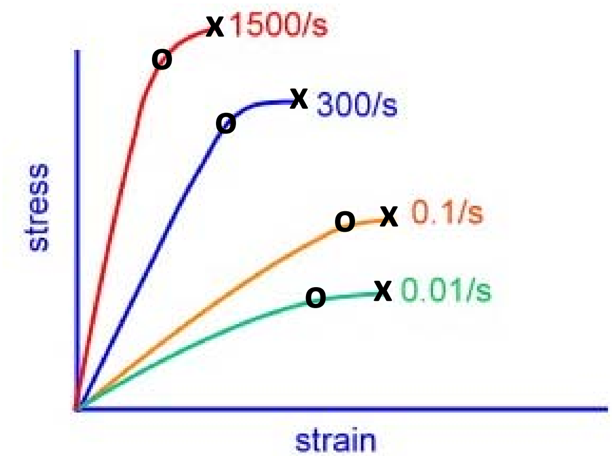
Introduction

- **Dynamic Phases of Flight**
  - Launch
    - All proposed vehicles launch with crew laying on their backs (eyeballs in accelerations)
  - Abort
    - Primarily X-axis loads (Eyeballs in)
  - Reentry
    - Primarily X-axis loads (Eyeballs in)
    - May have transient dynamics due to parachute deploy
  - Landing
    - The landing mode is specific to the vehicle design.
      - Water Landing
      - Land Landing
      - Runway Landing

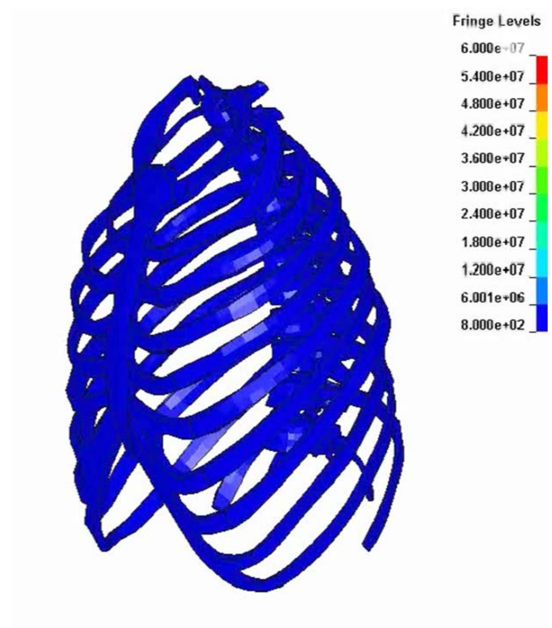
- **So how do you relate vehicle dynamics to injury risk?**

Credit: SNC

- **Material failure is related to its stress-strain relationship**
  - Before the yield point (o), any deformation of a material under stress will return to its original shape. Beyond the yield point, the material begins plastic deformation which will not return to its original shape when the stress is removed. At the ultimate tensile strength (x), the material fails

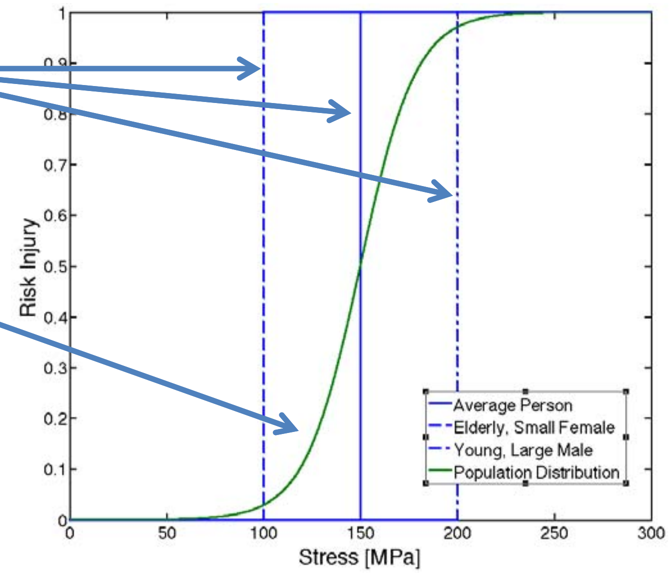


- **Tissues of the human body**
  - Have various stress/strain relationships
  - Are rate dependent (stiffer with higher loading rates)
  - May differ depending on loading direction
    - i.e. for bone, axial strength is higher
  - May have complex material properties depending on the body region and interactions between tissues
    - Injury modes are dependent on these complex interactions



What is Injury?

- Injury can be defined as the stress-strain value where the material will fail or break (ultimate strength), which varies with individuals and loading rate
- Because each individual is different, this value is a distribution for a general population. This gives varying injury risk relative to a given stress-strain (i.e. at a give stress-strain, 5% of subjects may experience a failure)
- However, the stress/strain in a human body cannot be directly measured, so alternative assessment methods are used such as forces, moments, deflections, and accelerations



Two Approaches to Mitigate Injury

Determine Injury Risk Function

- Correlate injury outcomes with assessment response
- Difficult to determine true injury risk at very low levels because the underlying distribution is not known
- Human surrogates introduce uncertainty

Determine Human Tolerance

- Use binomial statistics to reach desired confidence level and relate to assessment response
- Does not determine injury threshold or risk of injury, just whether a level is safe
- Greater confidence in safety
- May be conservative

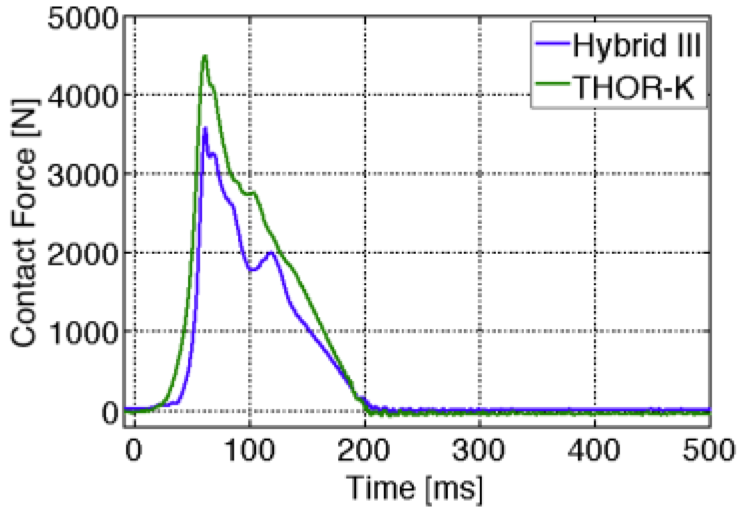
Injury Assessment Method Comparison

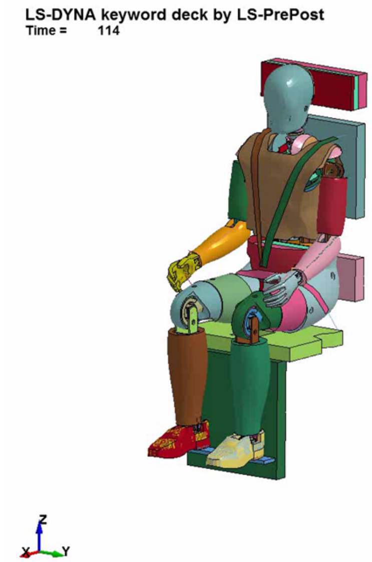
	Humans			Human Surrogates		Numerical Models		
	Human Volunteers	PMHS	Human Exposure	ATD[2]	Animal	Brinkley Dynamic Response Model	ATD[2] Numerical Model	Human Numerical Models
Extrinsic Injury Risk Factors								
Vehicle Dynamic Profile	Yes	Yes	No[3]	Yes	Yes	Yes	Yes	Yes
Seat & Restraints	Yes	Yes	No[3]	Yes	No	No[4]	Yes	Yes
Suit & Helmet	Yes	Yes	No[3]	No[5]	Partial	No[4]	Yes	Yes
Intrinsic Injury Risk Factors								
Age	Yes	No[6]	No[3]	No	No	No	No	Possible[7]
Gender	Yes	Yes	No[3]	No	No	No	No	Yes
Anthropometry	Yes	Yes	No[3]	Yes	No	No	Yes	Yes
Spaceflight Deconditioning	No	Possible[8]	No	No	Yes	No	No	Possible[7]
Other Considerations								
Anatomy	Yes	Yes	Yes	Partial	No	No	Partial	Yes
Physiologic Response	Yes	No	Yes	No	Yes	No	No	Yes
Injurious Testing	No[3]	Yes	Yes[3]	Yes	Yes	Yes	Yes	Yes
Direct Observation of Injury	No	Yes	Yes	No	Yes	No	No	No
Technology Readiness Level[9]	High	High	High	High	High	High	Moderate[9]	Low

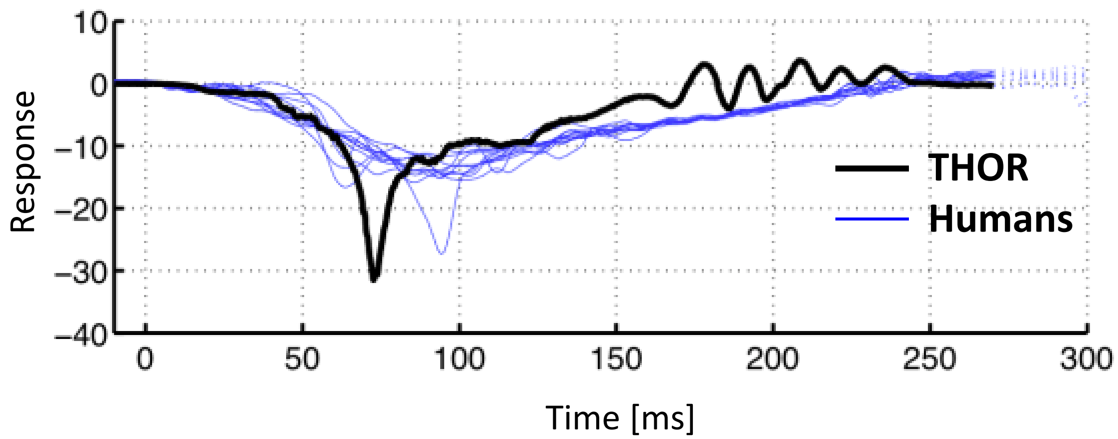
[2] Anthropomorphic Test Devices
[3] Not possible prospectively
[4] The Brinkley Dynamic Response Model was validated using specific seat and restraint setups and dynamics. The model may not predict injury accurately when extrapolating beyond this setup and dynamics.
[5] Not possible to assess localized injury potential
[6] Although possible prospectively, very difficult in practice due to limited subject pools
[7] Currently Available Human numerical models do not specifically address these factors, but could be modified to simulate the increased risk of injury
[8] Selection criteria could be used to select only subjects with similar bone mineral density (BMD), although this is not a true representation of spaceflight deconditioning.
[9] Technology Readiness Level (TRL) is a measure of how ready each method is for immediate use. ATD models are at various levels of TRL depending on the solver, ATD family and size

Human Surrogates & Models

- Because each surrogate/model may respond differently than a human, the reaction forces may have different dynamics
- To determine Injury Assessment Reference Values (IARVs), the surrogate/model must be subjected to the same conditions as the human cases used to develop the IARVs
- Because of this, any IARVs are specific to that surrogate/model and are not valid for other surrogates
- If the surrogate/model is not biofidelic, the IARVs may not be valid across a range of loading rates because human body tissue responses are rate dependent



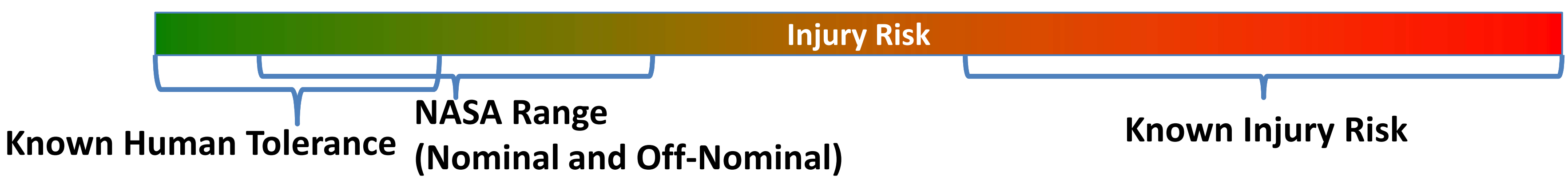




Injury Risk

Environment	P(impact)	P(inj)	P(total)
Military	Low	Medium	Low
Automotive	Remote	Med-High	Low
Race Car	Low	Medium	Low
Spaceflight	Certain	Low	Low

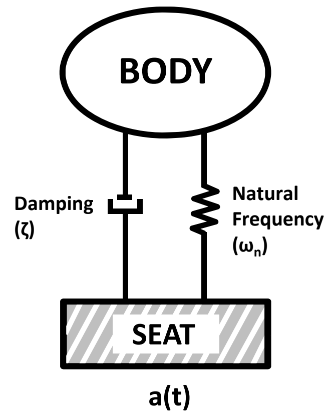
- **The Brinkley Dynamic Response Criterion is based on human volunteer testing**
  - Low risk level is based on human tolerance, but were not developed using statistical methods
- **Current ATD injury assessment reference values (IARVs) are based on automotive injury risk functions**
  - These functions are optimized for more severe and higher probabilities of injury than are needed for NASA use
  - Little information is available between the range of known human tolerance and injury risk

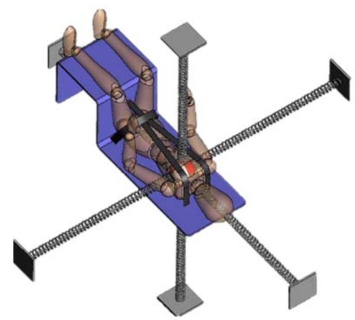


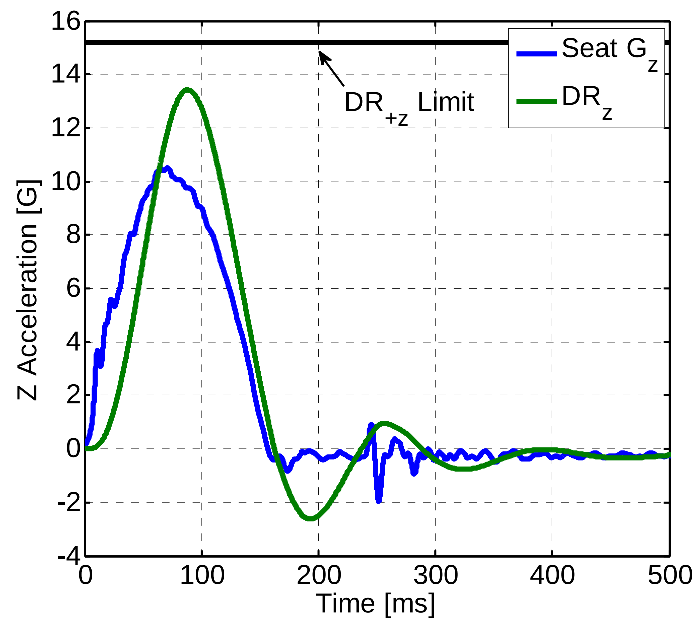
Where we are today

Brinkley Dynamic Response Criterion (BDRC)

- **Dynamic Response (DR)**
  - Estimates the acceleration of the human body
  - A single degree of freedom lumped mass model
  - Calculated independently in each direction
  - Responses are highly specific for seat used in development
- **Injury Risk Criterion (β)**
  - Preset DR limits in each direction estimate the injury risk
  - Limits based on limited statistical analysis of injury data
  - Estimates an injury risk but not severity
    - Low: 0.05 to 0.5%
    - Moderate: 0.5 to 5%
    - High: 5 to 50%
- **Model Accuracy Varies by Direction**







Direction	DR (Response)	β (Injury Risk)
+X (rear)	Insufficient data, so –X model used	Human injury exposure
-X (frontal)	17 male subjects only at 10G, age 22-35	Human injury exposure
±Y (lateral)	11 male, 2 female, only at 8G, age 22-34	Expert opinion
+Z (spinal)	57 yo cadaver (ω_n) and 8 males (ζ), age 29-47	Ejection injury rates
-Z (headward)	11 male, 1 female, only at 10G, ages 22-37	Expert opinion

Brinkley Model Ground Rules

- **The following ground rules are intended to assure a vehicle design meets the underlying assumptions necessary to apply the Brinkley Dynamic Response Model (BDR)**
- **Proper restraint**
  - The BDR was developed with a specific restraint configuration. Similar restraints must be correctly used to apply the model
- **Flail considerations**
  - The model was developed with arm and leg restraints. Injury due to flail is not captured by the BDR injury prediction, so flail protection is required in addition to the BDR
- **Seating support**
  - The model was developed with data obtained through human subject testing in specific seat geometry. Changes in seat geometry has been shown to increase the risk of injury (not captured in model predictions).
- **Amplification**
  - Improper seat cushioning has been demonstrated to cause amplification of loads transmitted to the crewmembers which can invalidate the BDR predictions
- **Suit Considerations**
  - Research and testing have shown that suit elements (e.g. metallic mobility joints, helmets, etc.) can produce injuries not predicted by the model.
- **Deconditioning**
  - Additional deconditioning factors are needed to protect crews due to long-duration spaceflight deconditioning (unless countermeasures are demonstrated to mitigate the effects on impact tolerance)

Brinkley Model Limitations

- **Even with the ground rules, there are limitations of the model that necessitate supplemental requirements**
- **Model validation**
  - The model is well validated in some directions, but not others
- **Sex differences**
  - The model was developed primarily with young, male military volunteers. Females are known to be at greater risk of injury (particularly in the neck)
- **Age effects**
  - Older occupants are at a greater risk of injury due primarily to changes in BMD.
  - We feel this risk is controlled by the current BMD flight selection standards
- **Anthropometry effects**
  - Smaller occupants have a greater risk of some particular injury given the same dynamics
- **Military training**
  - Military subjects have been shown to have a 15-20% higher BMD than the general population.
  - Because astronauts are more like the military population than the general population, this risk is believed to be controlled
- **Head Supported Mass / Helmet Mass**
  - The helmet can be a source of injury if it is not within the original constraints used during model development (Mercury helmet was used in many of the original tests)

Hybrid III Anthropomorphic Test Device (ATD)

- **The Hybrid III was developed in the 1970's for frontal car crash testing**
- **It has been adapted over the years for various industries**
- **Several configurations are currently available including**
  - Available in 5th female, 50th male and 95th male adult sizes
  - Straight and curved spine designs
  - Sitting and articulating pelvis designs
  - Various heads available

- **Several commercial numerical models are available for the Hybrid III**
  - COTS FE models of ATDs do not include some of the configuration options
  - Evaluate of the fidelity of the various COTS models is needed
  - FE ATD models which include pressure suit elements do not currently exist
- **Limitations**
  - The Hybrid III is not intended for lateral use
  - The neck responses are not biofidelic in any direction
  - Chest is very stiff
- **New Occupant Protection requirements levied on MPCV and CCP include the use of the 5th and 95th percentile Hybrid III**
  - Further investigation of sensitivities to variations in ATD configurations, seated versus articulated pelvis and straight versus curved spine, is needed

Hybrid III Limits

Injury Assessment Reference Values (IARV) Limits

ATD Metric	ATD Size[1]	Non-Deconditioned		Deconditioned	
		Nominal	Off-Nominal	Nominal	Off-Nominal
HIC 15	5th Female	375	525	375	525
	95th Male	325	450	325	450
Head Rotational Acceleration [rad/sec^2]	5th Female	2,500	4,200	2,500	4,200
	95th Male	2,100	3,600	2,100	3,600
N_{ij}	5th Female	0.5	0.5	0.4	0.4
	95th Male	0.5	0.5	0.4	0.4
Peak Neck Axial Tension Force [N][2]	5th Female	890 – 1,840		765 – 1,580	
	95th Male	2,000 – 3,390		1,720 – 2,910	
Peak Neck Axial Compression Force [N][2]	5th Female	890 – 2,310		765 – 1,990	
	95th Male	2,000 – 4,360		1,720 – 3,750	
Flail	5th Female	Pass			
	95th Male	Pass			
Peak Lumbar Axial Compression [N][3]	5th Female	3,500	4,200	3,000	3,600
	95th Male	6,600	7,800	5,700	6,700

[1]The following ATDs shall be used to evaluate the metrics:

5th percentile female automotive Hybrid III

95th percentile male automotive Hybrid III with straight spine

[2]Values in table are evaluated at varying time durations as specified in J

[3]Required only if Occupant Response Amplification ground rule is not met by the design

Test versus Analysis

- **The NESC expert panel discussed test versus analysis for verification**
- **The team expressed concern over the fidelity of the current numerical models for verification purposes**
- **The NESC expert panel agreed to the following process:**
  - Assure the design meets the Stated Ground Rules
  - Analyze the design using the Brinkley Dynamic Response Model
  - Use Hybrid III Anthropomorphic Test Device (ATD) numerical models as prescribed by the requirements to conduct an analysis of the design cases
  - Select the worst cases for each metric
  - Conduct physical impact tests of the selected cases to verify design

NESC Review

- **The NESC assembled a panel of experts to review the proposed changes**
- **The panel unanimously concurs with the proposed changes to the requirements**
- **Panel Members**
  - Shean Phelps, Georgia Tech (former US Army flight surgeon)
  - Rick DeWeese, FAA
  - Joseph Pellettiere, FAA
  - Glenn Paskoff, U.S. Navy
  - Chris Perry, U.S. Air Force
  - Smith Johnston, SD
  - Mike Barratt, CB
  - Dustin Gohmert, EC
  - Nancy Currie, NESC
  - Chuck Lawrence, NESC
- **Ex-Officio Participants**
  - Susan Baggerman, HMTA MPCV
  - Jennifer Rochlis, HMTA CCP
  - Mark Baldwin, LM
  - Martin Annett, NASA LaRC

Research Plan

Risk Description & Current Mitigations

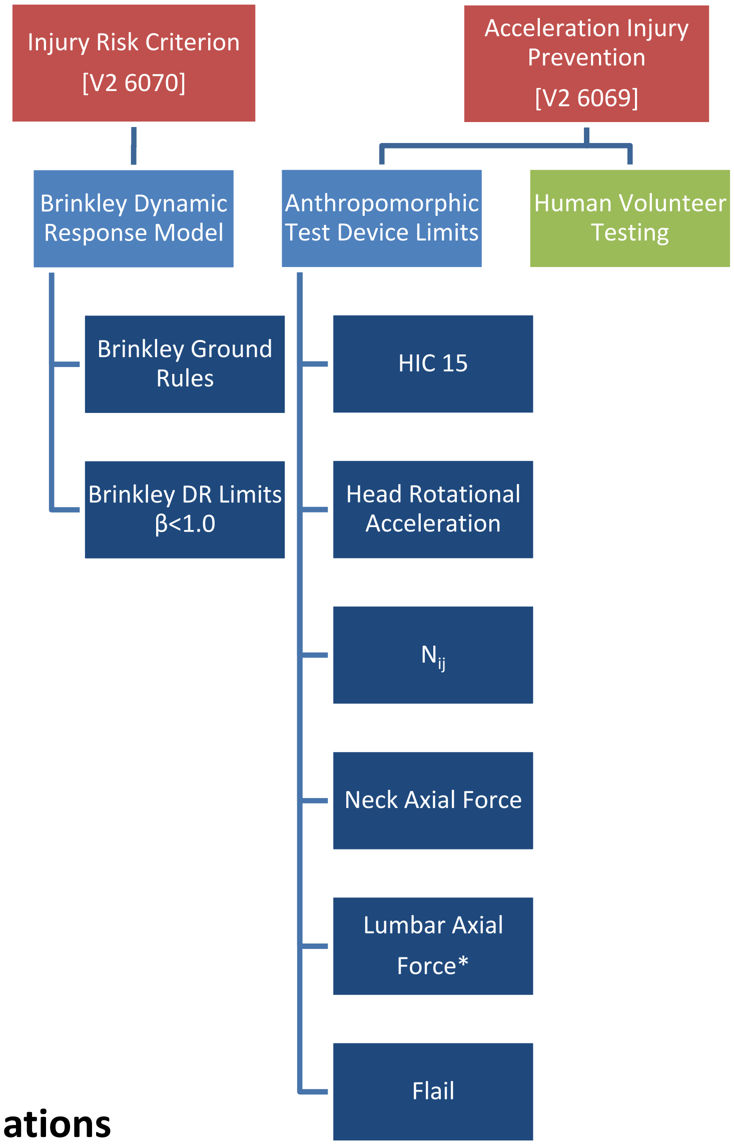
- **Risk Title**

  Risk of Injury from Dynamic Loads

- **Risk Statement**

  Given the range (e.g., magnitude, direction, and duration) of anticipated dynamic loads transferred to the crew via the vehicle, there is a possibility of loss of crew or crew injury during dynamic phases of flight including launch, abort, and landing.

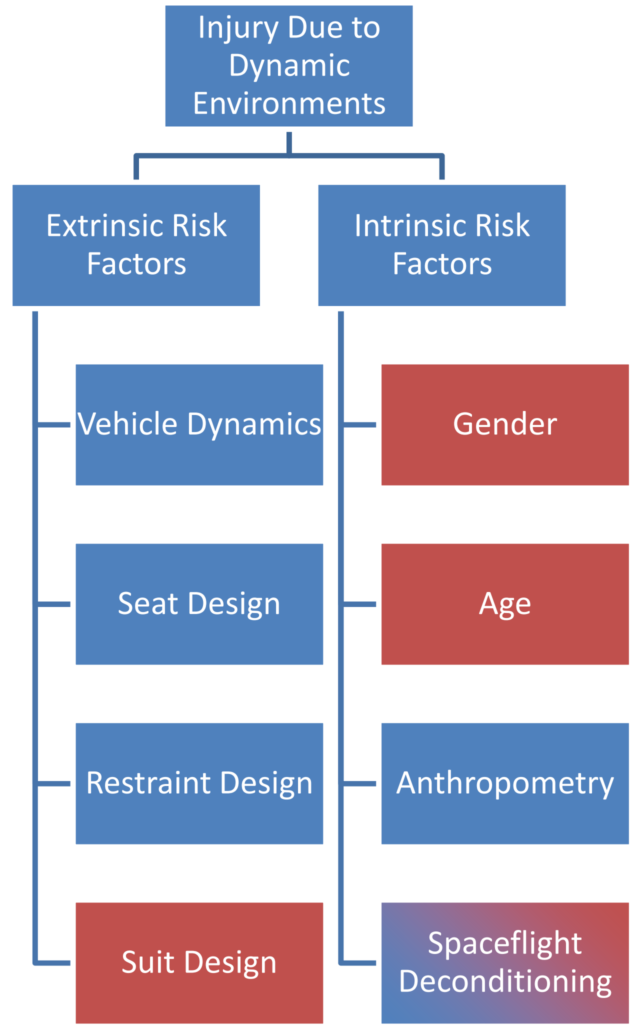
- **Current Mitigations**
  - Standards & Requirements
    - Brinkley Dynamic Response Criterion
    - Anthropomorphic Test Device (ATD) Injury Assessment Reference Values (IARV)
    - Sub-injurious Human Testing at Nominal Landing Conditions



Red Text: Proposed updates based on SRP recommendations

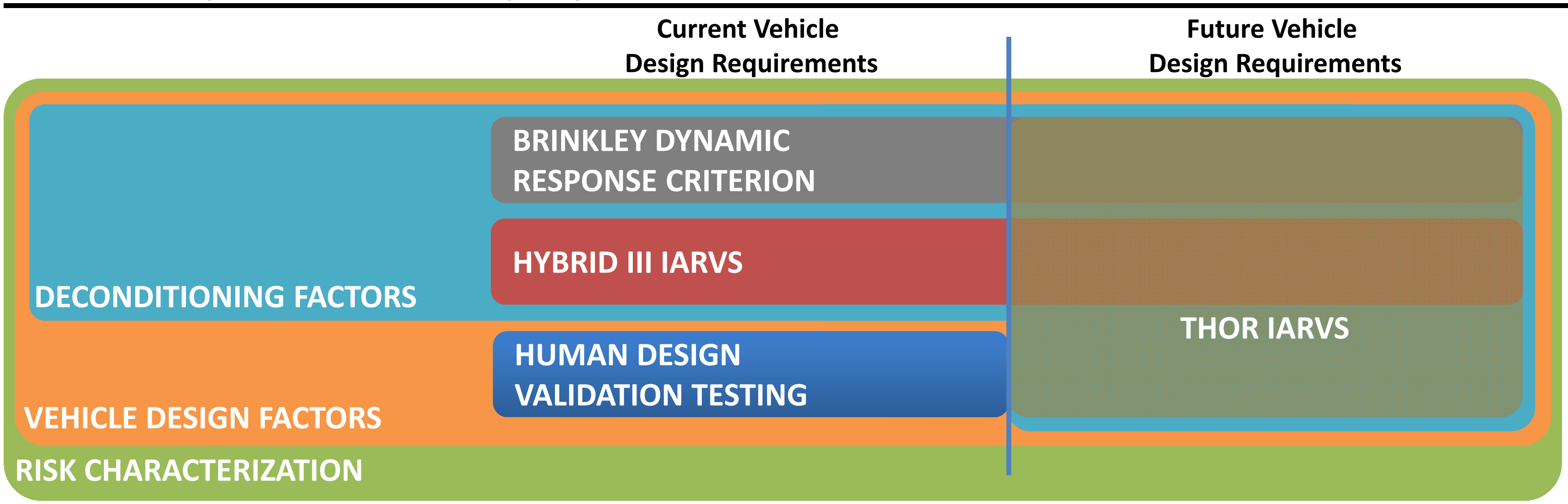
Limitations with Current Approach

- **Current requirements do not adequately address all of the risk factors (red boxes)**
  - BDRC primarily addresses vehicle dynamics
  - Hybrid III ATD addresses vehicle dynamics, seat and restraint design, and anthropometry
  - FE ATD models which include pressure suit elements do not currently exist
  - Current mitigations do not directly address gender and age differences
  - Spaceflight deconditioning factors are based on DXA data and may not be indicative of the true risk
- **Because of these limitations, certification for flight requires human testing for ALL vehicle designs (per SA-13-061 HMTA Position Memo)**
- **Current operational experience with Soyuz shows a risk of injury due to dynamic loads to be >1% (Partially controlled)**
  - More information is needed to understand how the current requirements relate to the Soyuz and whether the current injury rate is predicted by these requirements



Research Plan Overview

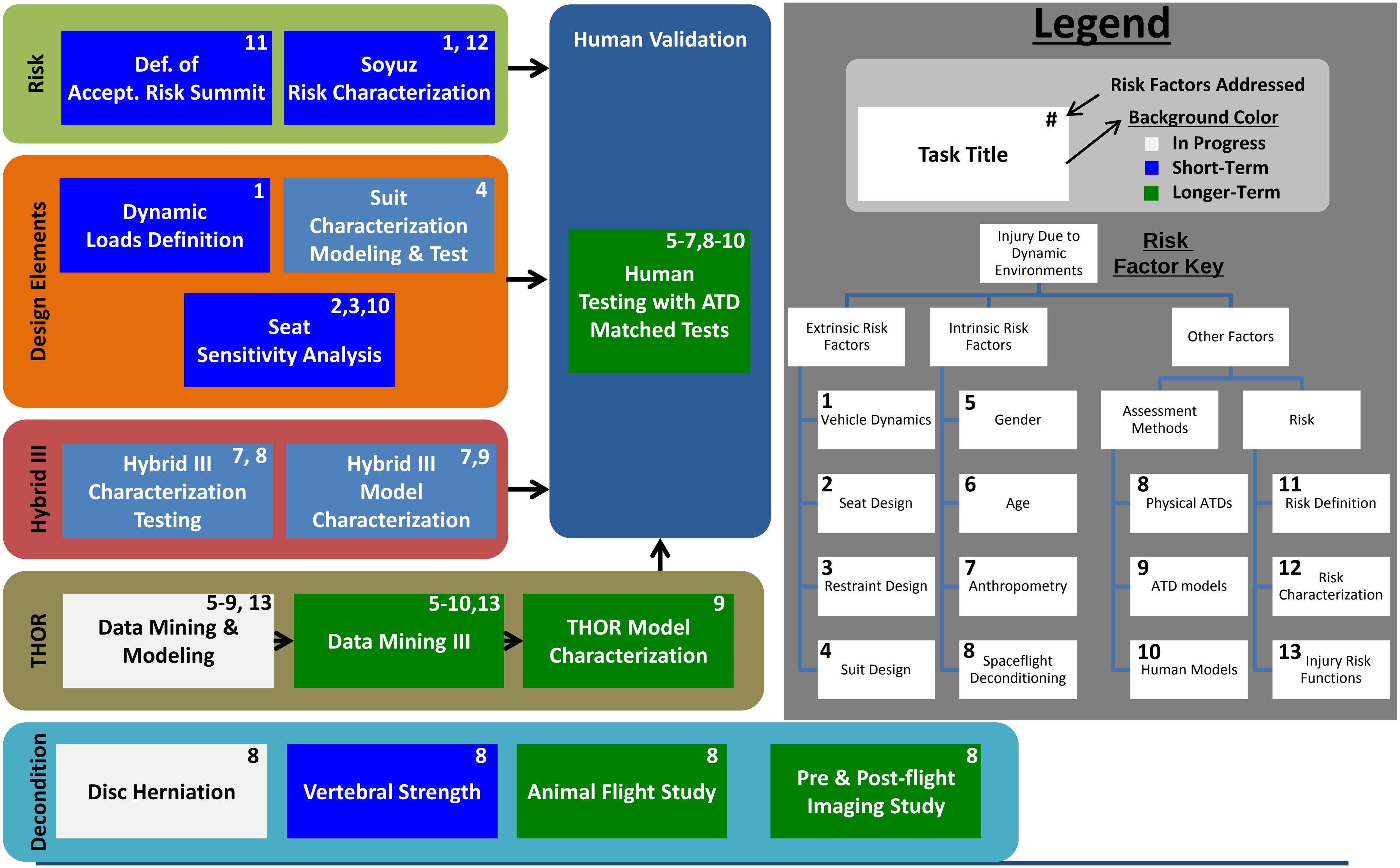
- **In order to mitigate the risk of injury to crew, a phased approach is proposed**
  - Conduct research in the near term which improves the current requirements
  - Conduct additional research to alleviate the human testing requirement and improve injury mitigation with better standards and requirements
- **The Research Plan is divided into five parts**
  1. Characterize the Risk with the current vehicle and current design requirements
  2. Characterize Design Impacts by studying the effects of various design features on injury risk
  3. Characterize the Hybrid III to mitigate risk in the short term
  4. Revise Deconditioning factors using current and future research information
  5. Develop new IARVs based on the THOR and <u>replace</u> the Human testing, and <u>possibly replace</u> the Hybrid III and Brinkley requirements as well



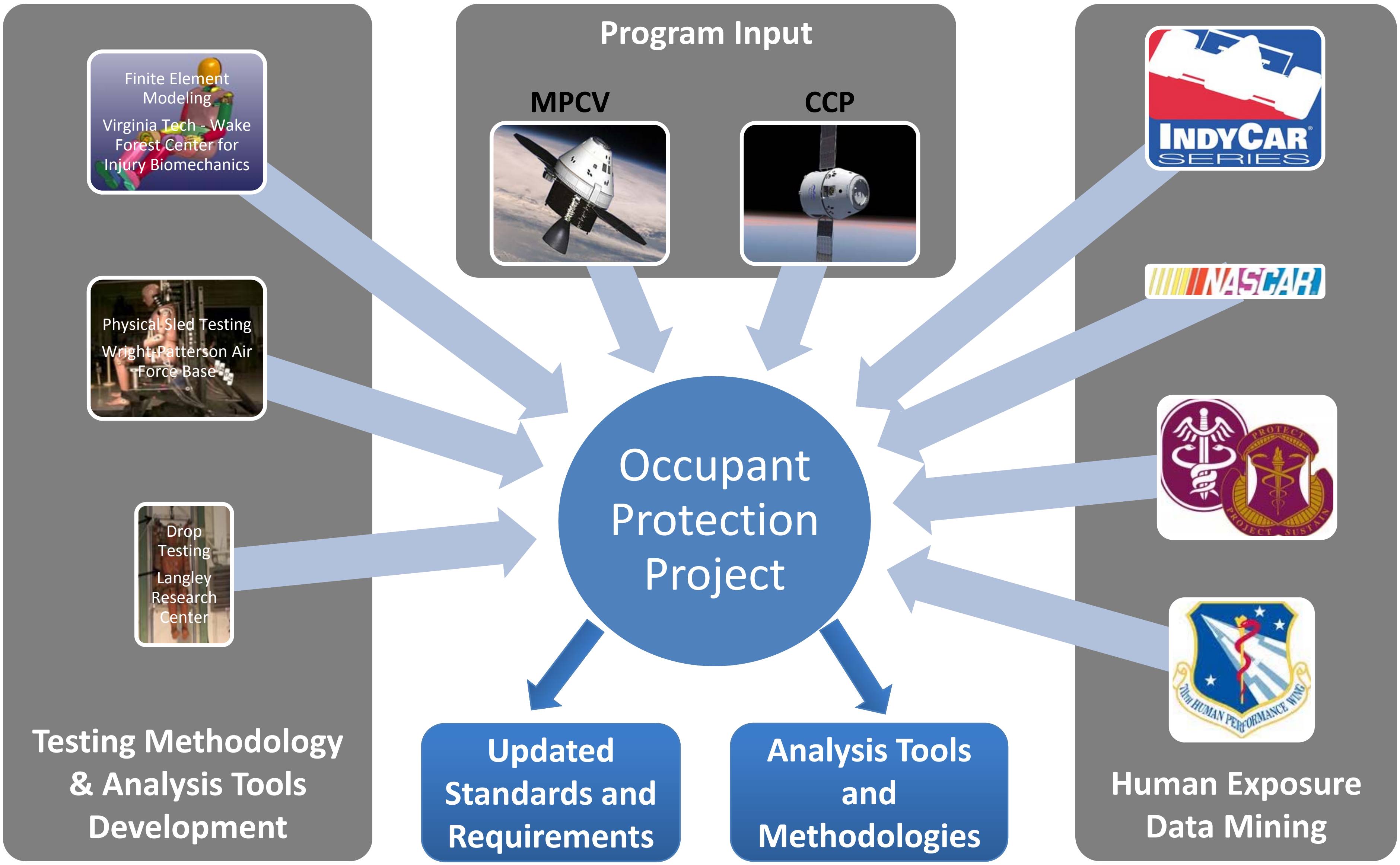
THOR Anthropomorphic Test Device (ATD)

- **Test Device for Human Occupant Restraint (THOR)**
- **Background**
  - Development began in the 1990s and has continued through the present to refine the design
  - Soon to be proposed by NHTSA as basis for car safety regulations
- **Design Highlights**
  - Designed for frontal and oblique car crash testing
  - Designed to be biofidelic in the neck and chest responses
  - Includes more measurement capability
  - More sensitive to low energy dynamics
  - Spinal structure is a better approximation to human than Hybrid III
  - Best multi-axial ATD available today
- **Drawbacks**
  - Only available in one size (50th percentile male), although a 5th percentile female is planned in the future
  - Not as readily available as the Hybrid III (less than 10 available today)
  - Expensive to upr

Research Philosophy



Current Collaborations

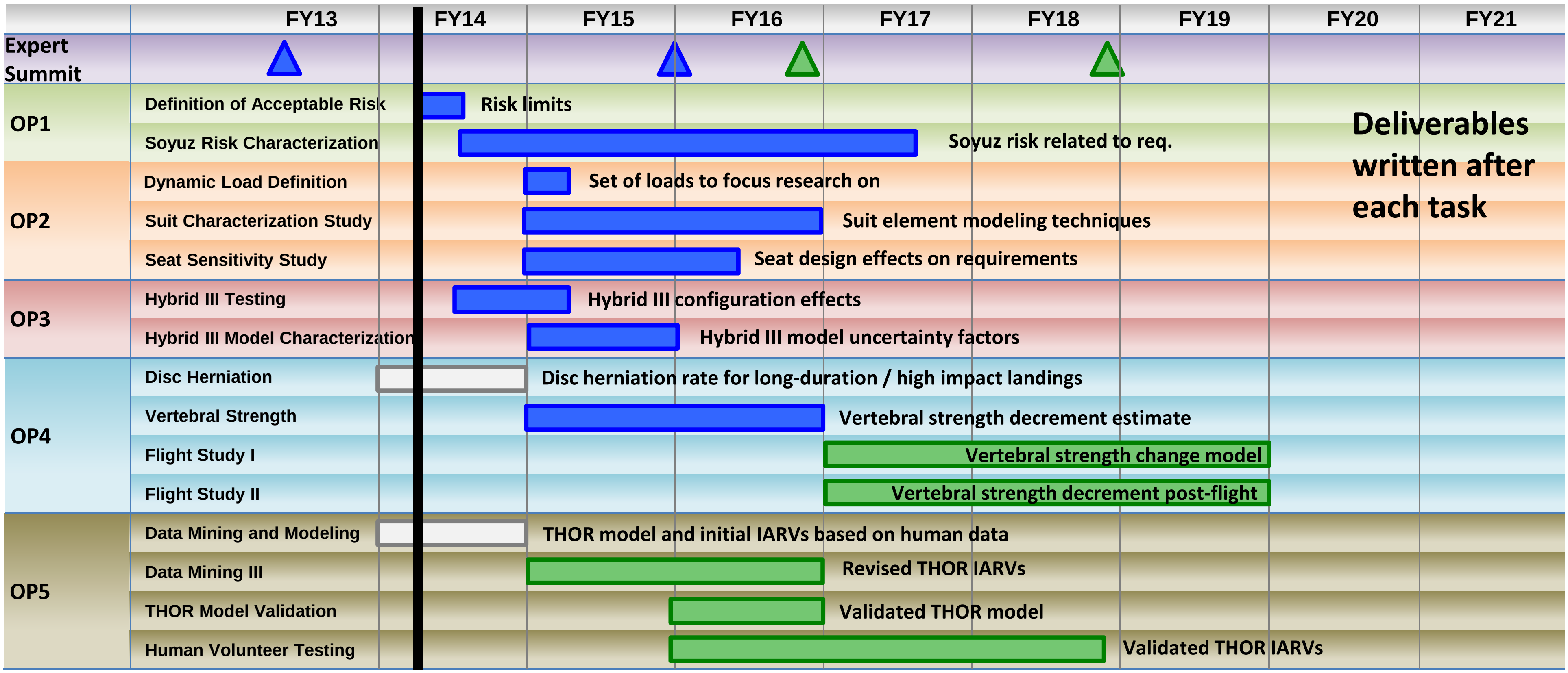


Gap Structure

Gap	Title	Description	Task	Gap Type
OP1	Risk Characterization	Determine the desired level of risk and efficacy of current mitigations	Def. of Acceptable Risk Summit	Risk Definition
			Soyuz Risk Characterization	
OP2	Design Effects Characterization	Understand the effects of design elements on injury risk	Dynamic Load Definition	Knowledge
			Suit Characterization Study	
			Seat Sensitivity Study	
OP3	Hybrid III Characterization		Characterization Testing	Tool Development
			Model Characterization	
OP4	Deconditioning Factor	Determine effect on dynamic breaking strength	Disc Herniation	Knowledge
			Vertebral Strength	
			Animal Flight Study	
			Pre- and Post-Flight Imaging Study	
OP5	THOR IARV Development	THOR ATD IARVs developed to replace human testing, and possibly BDRC and Hybrid III	Data Mining and Modeling	Knowledge
			Data Mining III	
			Model Validation	
			Human Volunteer Testing	

Pad
Abort

Notional Schedule



Summary

- **Current Occupant Protection Requirements are based on the best information available today**
- **Because of the uncertainty associated with the requirements, human testing at nominal levels is required for flight certification**
- **The Occupant Protection research plan is a phased approach**
  - Conduct research in the near term which improves the current requirements
  - Conduct additional research to alleviate the human testing requirement and improve injury mitigation with better standards and requirements
- **The Research Plan is divided into five parts**
  1. Characterize the Risk with the current vehicle and current design requirements
  2. Characterize Design Impacts by studying the effects of various design features on injury risk
  3. Characterize the Hybrid III to mitigate risk in the short term
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Backup Slides

A Great Example

2009 Chevy Malibu

3415 lbs
70.3” long
191.8” wide
112.3” wheelbase

Vs.

1959 Chevy Bel Air

3600 lbs
79.9” long
210.9” wide
119” wheelbase

Play Video

Results

<u>Moral of the story</u>: Controlling the energy that gets to the occupant doesn't tell the whole story. The design influences the outcome.

Other Links

- Ejection Seats
- http://youtu.be/CBL-kSCr4e0
- http://youtu.be/MgcPhl1UIhA
- http://youtu.be/e-RcMEDLu7Y
- Embrace Commercial
- http://youtu.be/t2o1oJ1zk_w
- Car Crash Tests
- http://youtu.be/lB0araA0T_k (F-150)
- http://youtu.be/sKSPxQjPOm0 (Smart Car)
- http://youtu.be/Bnt5DHnp31I (Toyota Previa)
- Rocket Sled
- http://youtu.be/lehHilNad3A
- http://youtu.be/qdp4gxfwlv0
- Stapp (2:35)
- http://youtu.be/s4tuvOer_GI